Nondestructive Spent Fuel Characterization with Semiconducting Gallium Arsenide Neutron Imaging Arrays

Agreement Number DE-FG07-98ID13633

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Report Period: July 1, 1998 – June 30, 1999

Overall Project Goal: The goal of this NEER research project is to develop a safe, convenient, and semi-portable inspection system for characterizing fuel burnup in irradiated nuclear fuel elements. This project utilizes unique properties of antimony/beryllium photoneutron sources with the extensive radiation hardness of gallium arsenide semiconductor devices. Analytical methods will be developed to determine characteristics of spent fuel elements from a combination of passive and active neutron radiography data obtained with the GaAs detectors.

Phase I

Goals: The primary goal of Phase 1 has been to develop an optimized detector design for the GaAs semiconductor neutron devices, in particular, in the composition and structure of the neutron absorber film, and to determine the radiation hardness of the detector arrays. In addition, lattice physics analysis has been performed to determine localized fuel burnup characteristics from tomographic neutron radiography data for irradiated fuel elements.

Task 1: Develop an optimized detector design and establish detector radiation hardness

Accomplishments: The bulk of the effort during Phase 1 of the project was dedicated to developing an optimized detector design and determining the radiation hardness of the detector arrays. Boron-10 coated linear arrays from bulk GaAs wafers have been designed and fabricated. An additional funding of $40,000 for the evaporator, to supplement the DOE allocation of $20,000, was obtained. The machine was designed and ordered in August 1998. Due to purchasing problems, the machine delivery was delayed until February 1999. The evaporator has now been successfully installed and calibrated, and fabrication of several different detector designs has been accomplished. The new GaAs imaging devices have two linear arrays each of 8, 16, or 32 pixels, giving each chip a set of 16, 32, or 64 total pixels. Three pixel sizes are designed into the first GaAs chip manufacturing processes, which include sets of (30 μm x 300 μm) pixels, sets of (200 μm x 500 μm) pixels and sets of (500 μm x 1000 μm) pixels. Arrays will either be mounted end to end or linearly scanned to cover the width of the fuel element in actual implementation of the devices during Phase 2 of the project.

Theoretical calculations have been performed on several additional neutron/charged particle converters other than ^{10}B and several different physical designs. For front-coated devices, the maximum theoretical efficiency for ^{10}B films is achieved at a thickness of 2.4 μm, whereas the maximum efficiency for ^{6}LiF films is achieved at 26 μm of material with only a modest 10% efficiency increase relative to ^{10}B coated films. Manufacturing accurate film coatings that are greater than a few μm in thickness is difficult, hence ^{10}B coated devices are clearly easier to fabricate. Analysis of pure ^{6}Li films indicates that single front-coated device can yield neutron detection efficiencies almost three times greater than that achievable with ^{10}B and ^{6}LiF films. Yet, such an increase in efficiency comes at the expense of depositing films that are 100 μm thick, which is even more difficult to achieve than that required of ^{6}LiF films. Additionally, pure ^{6}Li is very reactive and must be encapsulated before the device can be exposed to air. Hence, the handling ease of ^{10}B and ^{6}LiF far outweighs the gains realized by utilizing pure ^{6}Li for the neutron reactive film. From the calculations, GaAs detectors coated with pure ^{10}B for the neutron converter continues to be the main design for the neutron detector structure.

Numerous detector arrays are being studied to obtain a relatively wide statistical database. To offset the delay imposed by the late evaporator delivery, GaAs detector radiation hardness tests have been accelerated by irradiating the arrays at in-core irradiation positions in the 2.0-MW Ford Nuclear Reactor (FNR) at the University of Michigan. These positions have neutron fluxes on the order of 10^{12} neutrons/cm^2·s. Previous generations of these detectors have been continually irradiated in excess of 3000 hours in a special beam port at 1.7 x 10^6 neutrons/cm^2·s and 1.1 rad/hr gamma ray exposure without observable change in operating characteristics. The exposures are being varied and leakage currents, bias voltages and pulse height responses are being documented as a function of total gamma ray and neutron exposure. A 20-kCi ^{60}Co source is being used for accelerated gamma ray hardness tests. Device performance is being documented at various cumulative gamma ray doses until failure. These experiments will be used to determine both the catastrophic gamma ray and neutron irradiation limits for the GaAs detectors.

In addition to radiation hardness tests, the GaAs detectors are being investigated for neutron and gamma ray detection efficiency. A set of GaAs detector arrays is being tested in a double copper diffracted neutron beam to document neutron detection efficiency in the absence of a large gamma background. The detectors will subsequently be tested in a neutron beam port with both high gamma and neutron components in order to determine the ability of the detectors to discriminate between gamma ray signals and neutron signals.

Task 2: Develop methods to determine fuel characteristics from neutron tomography

Accomplishments: The basic approach we plan to use to determine the characteristics of spent nuclear fuel involves a combination of passive and active neutron interrogation techniques using GaAs detectors with neutron reactive films developed under Task 1. As the first step in studying an optimal way to determine spent fuel characteristics from neutron reaction rates measured by GaAs(^{10}B) detectors, fuel depletion calculations have been performed for typical FNR fuel elements with the WIMS collision probability code. Analysis of few-group macroscopic cross sections obtained for the entire fuel elements as a function of fuel burnup indicates that the absorption cross section depends weakly on fuel burnup. This suggests the desirability of determining, from detector signals, the fission cross section of the fuel element, which is naturally a sensitive function of fuel burnup.

Our analytical approach requires the determination of the ^{244}Cm concentration of any fuel mass through measurements of its spontaneous fission (SF) rate, which is essentially proportional to the fuel burnup. Determination of the SF rate in passive tomography, as well as accounting for induced fission contributions to the GaAs(^{10}B) detector response in active tomography, would require creative detector arrangements, including the placement of an iron filter and/or a moderator film in front of the boron absorption layer. With the iron filter, 24-keV neutrons from the Sb/Be source penetrating the fuel element will be selectively detected. In contrast, with the moderator film, fission neutrons would interact first in the moderator layer before undergoing capture in the boron film to produce charged particles, which will eventually be detected in the semiconductor detector. The placement of different thicknesses of the moderator film may be considered transformations of the absorber reaction cross section so that the determination of the incident beam intensity and spectrum would amount to the unfolding of neutron flux spectra through multiple foil activations. Development of the detector response function algorithm to represent the detection of fission neutrons in the semiconductor detectors will require considerable effort in Phase 2 of the project.

As part of the effort to study burnup characteristics of FNR fuel elements through WIMS calculations, inconsistencies in the few-group cross section edits of the WIMS code have been corrected. Since the latest version of the code, WIMS-D4M, reflects developments, often not well documented, at several different laboratories in the U. S. and Europe, considerable effort has been required, and will continue, to develop sufficient understanding of key segments of the code and to build in correct cross section collapsing schemes. Further modifications and improvements to the WIMS code will be required in Phase 2 to develop various semi-empirical conversion factors connecting measured neutron tomographic images and reaction rates to fuel burnup.